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Experimental Studies of MHD Dynamics in a RFP Magnetically Confined Plasma

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Studies of non-linear dynamics of MHD modes in the EXTRAP T2R reversed-field pinch experiment have demonstrated such phenomena as mode rotation, phase-locking and wall locking.

1. Introduction

The reversed field pinch (RFP) is a magnetic fusion device. It is similar to the Tokamak in that it is a toroidal configuration. However a significant difference between the RFP and the Tokamak is that for an RFP the toroidal magnetic field, B_ϕ , and the poloidal magnetic field, B_θ are about equal in magnitude whereas for the Tokamak, B_θ is much stronger than B_ϕ . In the RFP equilibrium, the toroidal magnetic field is maximum on the minor axis of the torus and decreases with increasing radius. At the plasma edge, the toroidal field is reversed relative to the field on axis. Clearly B_ϕ and B_θ vary strongly over the minor cross-section of the reversed-field pinch.

Tearing mode instability is a common phenomenon in magnetised plasmas. In the RFP configuration, the tearing modes exhibit very complex (and very interesting) dynamics. Indeed the non-ideal tearing mode fluctuations produce electric fields in a non-linear dynamo action. This well-known "RFP dynamo" sustains a part of the plasma current and is therefore important for sustaining the characteristic RFP equilibrium. The process that establishes the RFP equilibrium is called relaxation. The dynamic behaviour, described by Taylor [1], is based on the general principle that the plasma tends to relax toward a state of minimum magnetic energy. Magnetic reconnection (tearing modes), leading to a redistribution of helicity, characterises the relaxation.

The MHD modes in an RFP are characterised by a toroidal mode number n and a poloidal mode number m . The tearing modes are resonant with the magnetic field when $\mathbf{k} \cdot \mathbf{B} = 0$ where \mathbf{k} is the wave vector of the mode and \mathbf{B} is the equilibrium field. This resonance occurs on rational flux surfaces where the field winding number, $q = rB_\theta / RB_\phi$ has the value $q = m/n$. Since the fields vary strongly over the cross-section, there are potentially a large number of resonant modes in the RFP.

2. Experimental observations

A variety of MHD modes are predicted by theory and are indeed seen in experiments. Studies of tearing mode dynamics have been made in the EXTRAP T2R RFP located at the Alfvén Laboratory. The device is a medium-sized RFP with an aspect ratio $R/a = 1.24$ m /

0.18 m [2]. A unique feature of the device is that the conducting boundary, or shell, has a magnetic penetration time of about 6 ms, which is shorter than the pulse duration (20 ms) but much longer than the typical tearing mode growth rates. The RFP configuration is dependent on a conducting wall for MHD stability. The device is therefore suitable for the study of the effects of a non-ideal boundary on both ideal MHD modes and tearing modes.

For tearing modes, there is good agreement between linear MHD stability theory and the observed existence of the modes. The perturbations associated with the observed modes are $m=1$ (resonant on flux surfaces where $1/n = rB_\theta / RB_\phi$) and $m=0$ (resonant at the reversal surface where $B_\phi = 0$). The qualitative picture is that the tearing modes form magnetic islands lying on nested (resonant) toroidal flux surfaces.

The existence of the perturbations is predicted by linear theory but the dynamics of the modes that are experimentally observed is of course generally non-linear. Therefore the RFP is a very good device for the study of non-linear MHD mode phenomena. Examples of phenomena that have been experimentally studied in the EXTRAP T2R device are as follows [3]:

- Spectra of saturated mode amplitudes.
- Phase alignment (locking) of several modes to form a localised perturbation in the flux surfaces.
- Toroidal rotation of the modes due to viscous drag on the islands produced by the flowing plasma fluid, either in a phase-locked formation or with velocities independent of each other.
- Wall locking of the modes due to electromagnetic braking forces on the modes caused by stationary fields from currents in the boundary structure.

Saturated modes form magnetic islands that are immersed in the plasma. In Fig. 1 the power spectrum for $m = 1$ modes is shown as a function of the toroidal mode number n . The spectrum is derived from measurements of the magnetic perturbations made using arrays of pick-up coils placed at the plasma edge. Each mode is a Fourier harmonic of the total perturbation. The dominant n -numbers are in good agreement with the predicted values of n for the equilibrium magnetic field profiles. The amplitude of a

mode perturbation is typically about 1% of the equilibrium field.

Three or more modes can interact with each other and become phase-locked thus producing a localised flux surface perturbation at the point where the phases are aligned. The inter-mode electromagnetic forces between the different modes cause the phase-locking. This phase-aligned state often appears spontaneously and is quite robust. Indeed the phase-aligned configuration is frequently observed to rotate in the rest frame of the torus in a direction determined by the global toroidal flow of the plasma fluid.

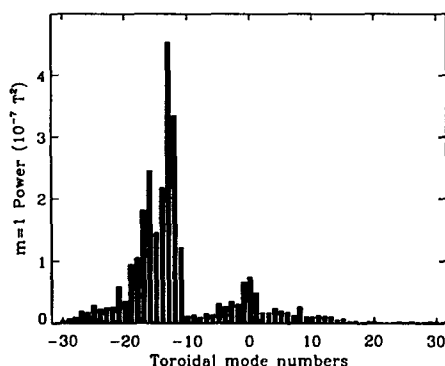


Fig. 1 Power spectrum of $m = 1$ tearing modes.

The degree of phase alignment can be quantitatively represented by a quantity called σ , which is the sine of the phase difference between two modes summed over a collection of at least three modes. If the phases are aligned, the sine of the phase difference between two modes is zero at that toroidal position. Three or more modes must be involved for the alignment to be non-trivial. The phase alignment is visualised by examining the inverse of this sum and a plot of $1/\sigma$ versus toroidal position and time is shown in Fig. 2.

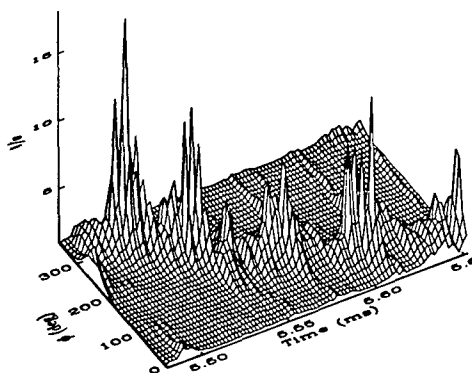


Fig. 2. The signature of phase-alignment, $1/\sigma$, as a function of toroidal position, ϕ , and time.

In Fig. 2 it can be seen that the phase aligned structure makes a complete toroidal revolution in about 150 μ s, which corresponds to a velocity of about 50 km/s. This

velocity is comparable to the $E \times B$ drift velocity of the plasma fluid in the toroidal direction.

The dynamics of a mode is affected both by viscous forces due to plasma flow relative to the island and electromagnetic forces between the mode and other modes or between the mode and externally produced fields. For example, image currents in the in the close-fitting conducting boundary surrounding the toroidal pinch interact with the rotating perturbations causing a drag which slows down the rotation. Also, non-axisymmetric magnetic field errors due to ports or gaps in the conducting boundary produce electromagnetic forces on the modes that lead to wall-locking, which is a form of phase-locking to stationary features.

One extremely important phenomenon is the fact that rotation of tearing modes suppresses the radial component of the magnetic perturbation at the conducting boundary. In Fig. 3 the amplitude of the radial component of the $n = 12$ tearing mode and its helical phase velocity are shown as a function of time.

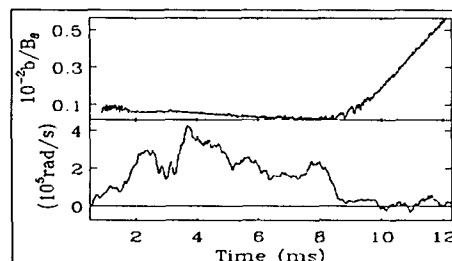


Fig. 3. Perturbation amplitude and helical phase velocity for the $n = 12$ tearing mode.

At about $t = 8$ ms, the rotation frequency goes to zero due to wall locking of this mode. The perturbation immediately starts to grow at a rate determined by the magnetic penetration time of the wall.

3. Concluding remarks

The presence of MHD activity of course negatively affects the confinement properties of the RFP experiments. The goal is to reduce the fluctuations. However the studies of the non-linear MHD dynamics that are carried out on RFP configurations contribute to the general understanding of MHD.

4. References

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